ABM and GIS Integration for Investigating the Influential Factors Affecting Wildfire Evacuation Performance

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Abstract –
Wildfires pose a big threat to human life and property safety. Previous studies on wildfire risk management focused mainly on understanding wildfire behaviour through computer simulations. Effective wildfire risk management also largely depends on the evacuation performance success. Computational tools tend to be the best approach for simulating wildfire evacuation emergencies as well. Therefore, this study proposes a comprehensive simulation framework that integrates Agent-based Modelling (ABM) and Geographical Information Systems (GIS) to efficiently simulate both human behaviour and transportation crowds. In particular, ABM bridges the technical gap between GIS and a multi-agent system (MAS) for simulation design efficiently and effectively. To study the evacuation performance (measured by the number of agents being sheltered or refused to evacuate), our modelling solution enables altering relevant model parameters in wildfire evacuation scenarios. The simulation outputs, as a result, can be used to evaluate the influential factors and further assist in effective evacuation planning. In particular, the following tasks are performed: (1) simulation of the influence of transportation crowds on evacuation performance; (2) evaluation of the effectiveness of public notification on evacuation success; and (3) comparison of the differences among various transportation means as well as their performances during a wildfire emergency. A case study is conducted to verify the simulation framework proposed in this study. The simulation outputs showed that the transportation crowds negatively impact on the evacuation performance, while public notification can enhance resident risk perception, thus assist in the evacuation efficiency. Finally, public vehicles such as public buses have the highest evacuation efficiency compared to other transportation means tested in this study.

Keywords – Wildfire Evacuation Simulation; Agent-based Modeling; Geographical Information Systems

1 Introduction

Wildfires pose a big threat to human life and property safety. The National Interagency Fire Center (NIFC) indicates that, over the past decade, an average of 67,000 wildfires resulted in 7 million acres burned annually [1]. In 2019 alone, there were 4.5 million U.S. homes were identified at high or extreme risk of wildfire, with more than 2 million in California alone [2].

To date, a number of studies have been conducted concerning the simulation of wildfire behavior. Catry et al. [3], for example, studied modeling and mapping the likelihood of wildfire ignition occurrence in Portugal. In [4], Westerling et al. applied statistical approaches to develop models for investigating the wildfire occurrence frequency affected by climate change in California. Linn et al. [5] utilized FIRETEC, a fire growth modeling software, to examine wildfire behavior with regard to different geographical regions. However, modeling wildfire behavior only is insufficient for effective wildfire risk management if both the number of injuries/fatalities and the level of property loss are expected to be minimized.

The success of evacuation performance is a critical factor in wildfire risk management. Due to obvious reasons and ethical concerns, computational simulation tends to be the best approach for studying human evacuation performance and transportation crowds during a wildfire. In addition to fire dynamics, a wildfire evacuation simulation mainly consists of human behavior as well as transportation modules [6]. To that end, this study aims to develop a simulation framework used for simulating both human behavior and transportation crowds simultaneously for wildfire evacuation performance assessment.

The remainder of the paper is organized as follows. Section 2 provides a comprehensive review of the research background. Section 3 details the proposed simulation framework and methodology. The experimental implementation is discussed in Section 4. The final section draws conclusions and offers recommendations for future research.

2 Research Background

A comprehensive review of the relevant literature on wildfire evacuation simulation is provided in this section. Human behavior critical to evacuation performance are also identified.

2.1 ABM and GIS for Evacuation Simulation

In outdoor evacuation scenarios, except for walking, transportation modules typically consist of various transportation means such as bicycles, private or public vehicles. To integrate human behavior and transportation modules into an outdoor evacuation scenario design, Agent-Based Modeling (ABM) technique is commonly used as it provides an environment where agents can be defined as any type of individual simulating their behaviors in mathematical, theoretical, and logical ways [7]. An ABM simulation scenario can reflect agent-to-agent interactions as well as agent-to-environment reactions simultaneously. To date, a number of studies have applied ABM to simulate outdoor emergency scenarios that covered a variety of hazards, including earthquakes [8], tsunamis [9], hurricanes [10], wildfires [11], and so on. Relevant to the study described here, Paveglio and Prato [11] proposed an ABM framework to investigate monetary and non-monetary attributes that influence human behavior and decisions with respect to wildfires. Therefore, it can be concluded that simulating human evacuation reactions and interactions is feasible using an ABM wildfire scenario design.

In addition to simulating human behavior and transportation modules, Geographical Information Systems (GIS) is a tool that can be used for outdoor evacuation simulation as it enables simulating agents' movements and evacuation process by providing the spatial data needed. In [12], Jumadi et al. developed a GIS-ABM simulation model to simulate the volcanic evacuation performance for risk assessment. In this case, ABM bridged the technical gap between the GIS tool and a multi-agent system (MAS) to simulate both human behavior and transportation crowds. Similarly, this study proposes to utilize an integrated ABM - GIS framework to simulate a MAS scenario, and to investigate the influential factors affecting the outdoor evacuation performance during a wildfire.

2.2 Influential Factors Affecting Evacuation Performance

This section provides a review of studies that have assessed wildfire evacuation performance with regard to a variety of human behavior. The following subsections summarize major findings of influential factors affecting human evacuation decisions and related choices in wildfire emergencies.

2.2.1 Public Notification

Public evacuation notification is critical in predicting the decision-making process of evacuees. A telephone questionnaire conducted by Strawderman et al. [13] revealed that, by signal detection theory, reverse 911 warnings had the best performance, and promoted a significantly higher rate of evacuation, compared with other evacuation warning sources. However, evacuees and public safety officials have different perceptions and concerns about the evacuation process [14]. In particular, McLennan et al. reviewed North American research into wildfire evacuation behavior published between 2005 and 2017 and summarized that: (1) even though mandatory evacuation is issued by the police department, many threatened residents are likely to delay evacuating due to the desire to protect their property; (2) some residents who are not on their property may seek to return; (3) warnings that are not sufficiently informative could be another cause for self-delayed evacuation; and (4) residents are likely to engage in information search rather than initiating evacuation actions. Overall, public notification promotes a higher risk-warning efficiency to encourage residents to evacuate. Nevertheless, residents are still likely to refuse to evacuate due to environmental factors and personal factors affecting individual risk perception as well as decision-making that result in evacuation delays.

2.2.2 Risk Perception

Personal factors with regard to risk perception in an emergency are complex and multidisciplinary. Toledo et al. [16] analyzed the influential factors affecting residents' decision-making process during a no-notice wildfire evacuation event that occurred in Haifa, Israel. They found that, in addition to the level of risk that the wildfire event poses to individuals, the influential factors related to household individuals (e.g. initial locations when a wildfire event happened) as well as their relatives (e.g. the number and locations of children or elderly individuals) significantly affect their evacuation decisions and associated movement patterns [16]. Besides, residents' evacuation efficiencies are heavily affected by their knowledge and experience with former wildfires [17], which should be considered in an evacuation scenario design as well.

2.2.3 Risk Mitigation

In addition to risk perception, personal behavior with regard to risk mitigation is another significant factor affecting the decision-making regarding resident evacuation performance. The study by Paveglio et al. [18] revealed that a relatively high proportion of residents are interested in passively defending or sheltering in their homes, with fewer residents favoring evacuation during a wildfire. In particular, resident evacuation preferences differ significantly due to the forest management strategy. For example, in [11], it was found that in the areas with significantly high rate of forest thinning, the residents chose to stay and actively defend their homes.

In [19, 20], it was found that a higher level of risk mitigation is positively associated with risk perception, including sufficiently informative wildfire information received from local volunteer fire departments, county wildfire specialists, as well as talking with neighbors about the wildfire. To conclude, residents who perceive higher levels of wildfire risk have undertaken higher levels of wildfire-risk mitigation to protect their property. Thus, the relationship between risk perception and risk mitigation undertaken is jointly and mutually represented in our simulation framework design.

2.2.4 Transportation Means

Means of transportation could have a huge impact on evacuation efficiency. In [21], Beloglazov et al. proposed a dynamic modeling approach to simulate the evacuation performance with regard to different evacuation locations. Li et al. [22] investigated the influence of evacuation timing for traffic based on a spatiotemporal GIS approach. In addition to evacuation locations and evacuation timing, movement velocities and loading capacities of various transportation means are significant as well.

Among typical transportation means (e.g. walking, bicycles, private or public vehicles), private or public vehicles account for higher velocities and loading capacities that are meant to have better evacuation performance. Undoubtedly, an efficient transportation network in a wildfire emergency could help residents to evacuate safely. However, frequent occurrence of transportation crowds caused by vehicles occupying the roads could highly impede the evacuation efficiency. Hence, the evacuation efficiency for a variety of transportation means should be further assessed to assist with evacuation strategies and management, and further improve the evacuation success.

2.3 Motivation and Objectives

Understanding the physical and social dynamics imposed by wildfires is fundamental to assessing and mitigating risks for residents [23]. Above all, human evacuation performance is greatly affected by public evacuation warnings, actions, and decisions related to risk perception and risk mitigation, and the variability of transportation means as well as their efficiencies. Those influential factors are critical to evacuation assessment, and pose challenges for modeling an effective wildfire evacuation scenario.

Several studies to date investigated human wildfire evacuation behavior. However, modeling solutions to predict and assess evacuation performance for wildfire scenarios is still at its infancy. Therefore, this paper proposes an evacuation behavior model embedded in an ABM-GIS simulation tool, AnyLogic [24], to simulate and investigate the impact of influential factors summarized in section 2.2. on wildfire evacuation performance.

In particular, (1) the influence of transportation crowds on the evacuation performance is simulated; (2) the effectiveness of public notification on the evacuation success is evaluated; and (3) the differences and efficiencies among various transportation tools during a wildfire emergency are compared. A comprehensive simulation framework, based on the influential factors derived from existing literature on human behavior in wildfires, is introduced to implement the proposed modeling solution. Finally, an experimental case study is conducted to validate the proposed modeling solution using AnyLogic.

2.4 Contribution

The main contribution of this study is a modeling solution for wildfire evacuation simulation in an ABM-GIS simulation framework. To assess evacuation performance (measured by the number of agents being sheltered or refused to evacuate), our modeling solution enables to modify relevant model parameters in wildfire evacuation scenarios. The simulation outputs, as a result, can be used to assess the impacts of influential factors (including the impact of public evacuation warnings, risk perception, risk mitigation, and various transportation means) affecting evacuation performance. Thus, the proposed modeling solution can further assist in safety management and effective evacuation planning for wildfire emergencies. To conclude, this study assesses the evacuation efficiency with regard to human life and transportation crowds in wildfire emergencies, which would ultimately help with wildfire evacuation education and safety strategies.

3 Research Methodology

The proposed simulation framework and modeling solution are introduced in this section. The findings of the recent studies on how to incorporate human wildfire evacuation behavior into an ABM-GIS simulation scenario [13-23] are considered and included in the framework design.

3.1 Simulation Framework

Figure 1 illustrates the simulation framework proposed in this study. The first step is to determine whether there is a wildfire or not. Next, the alert indicator about public evacuation warnings, either positive or negative, divides the scenario into four categories: 1) a true wildfire event and a mandatory evacuation issued by safety officials (true positive (TP)), 2) a no-notice true wildfire event (true negative (TN)), 3) mandatory evacuation issued for a false wildfire event (false positive (FP)), or 4) neither evacuation alert was issued nor a wildfire occurred (false negative (FN)). These four categories address particular evacuation outcomes, including different evacuation performance for a variety of scenarios.

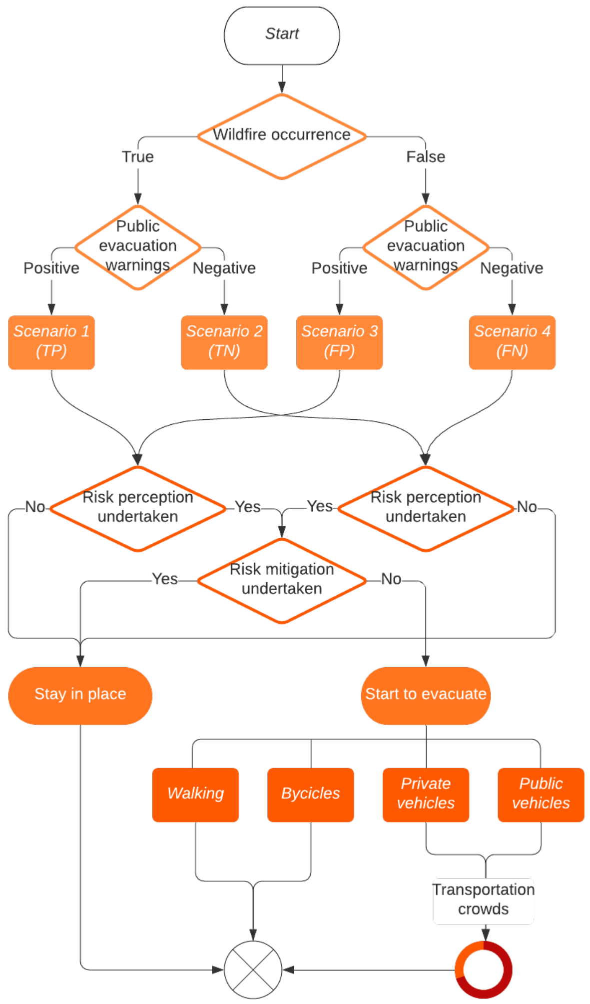

Figure 1. Proposed simulation framework

In the next step, agents' risk perception (true or false) is defined for each scenario. If the agents do not perceive any risk, they will choose to stay in place. The agents who perceive risk will either stay in place to actively defend their homes or start to evacuate. During the evacuation process, vehicles occupying the road may cause transportation crowds. In this case, there will be evacuation delays, which is incorporated in the movement process in our simulation design. The average velocities and capacities of typical transportation means in a wildfire emergency are summarized in Table 1.

Table 1. Designed parameters for various transportation means

	Average velocities (mph)	Common capacities
Walking	3-5	1
Bicycles	12-15	1-2
Public vehicles	30-45	20-50
Private vehicles	40-70	1-5

The final step is to analyze the simulation outputs, which present the number of agents either refusing to evacuate or being sheltered. These numbers can be used to assess agents' evacuation efficiency with regard to the effect of public evacuation warnings, risk perception, risk mitigation, and various means of transportation. Consequently, the impacts of influential factors affecting the evacuation performance are evaluated, which would ultimately help with wildfire evacuation education and safety strategies.

3.2 Modeling Solution

The ABM-GIS wildfire simulation scenario consists of the movement flow module and the geographical module representing the agents' movement process in chosen areas. The modeling software AnyLogic, which embeds the GIS tool, provides a powerful simulation environment, as it enables to simulate agent movement and evacuation process while providing the geographical and spatial data needed.

3.2.1 Modeling Parameters

The movement flow module presents the agent evacuation process. AnyLogic provides users a process modeling library, including various modeling parameters, to define agents' behavior. The agent movement flow in this study is designed based on the simulation framework shown in Figure 1. Hereby, Table 2 introduces several selected modeling parameters including their names, icons, descriptions, and properties of functions.

Table 2. Introduction of modeling parameters [24]

	Description	Function
Source 	A starting point of a process flowchart to generate agents.	Define agent location, arrival rate, and quantity, etc.
Select Output 	Two output ports to route agents.	Sort agents according to certain criteria.
Select Output5	Five output ports to route agents.	Split the agent flow into different

		transportation means.
Move To	Move agents to a new location.	Define agents' destination and movement speed.
Queue	A queue of agents waiting to be accepted by the next block in the flowchart.	Define the maximum capacity and agent location in a queue.
Sink	An ending point to dispose incoming agents.	Present the number of agents disposed.

3.2.2 The Movement Flow Module

Five agent types are defined in a wildfire scenario, including the residents and four transportation means including walking, bicycles, private vehicles, and public vehicles. By utilizing the process modeling library, the agents' behavior is defined in AnyLogic (Figure 2).

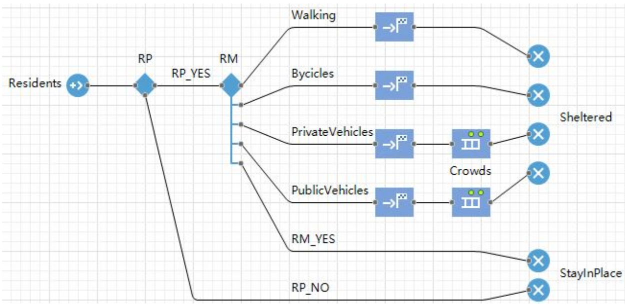

Figure 2. A simplified version of agents' behavior in AnyLogic

At the start of the movement flow, resident agents are sorted based on their judgments about risk perception and risk mitigation undertaken, namely RP and RM. Next, a portion of resident agents, who does not perceive the risk or prefer to self-defend their homes after risk perceived, is disposed to stay in place. The remaining resident agents start to evacuate using one of the four transportation means, which are predefined with different movement velocities and loading capacities summarized in Table 1. It is assumed that transportation crowds (i.e., vehicle flows exceeding the highway capacity) require the agents taking the vehicles to queue to be sheltered. In the meantime, other agents who evacuate by walking or bicycling move toward the shelters identified in the GIS map. AnyLogic allows presenting agents' movements as a 2D/3D animation and counting agents that are disposed by modeling parameters in real-time.

4 Experimental Implementation

To validate the practicality of the proposed modeling solution, an experimental implementation was conducted to simulate a hypothetical wildfire evacuation emergency.

4.1 Experimental Assumptions

4.1.1 Geographical Background

The CampFire in California [25], which occurred in 2018, was used as a geographical background composed of several GIS nodes: (1) the ignition node, namely Creek Camp Road, (2) the shelter node, namely Orland, and (3) four independent scenario nodes, namely Paradise, Oroville, Chico, and Willows, navigated based on their spatial attributes (Figure 3).

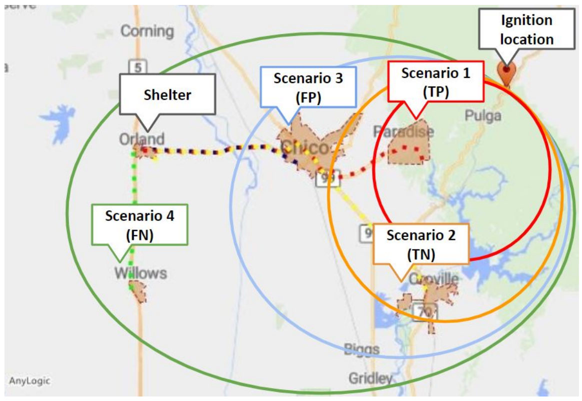

Figure 3. Geographical nodes navigated in the GIS tool embedded in AnyLogic

This study assumes the level of wildfire risk for each scenario depending on the spatial distance measured from the ignition node to those scenario nodes. In particular, the town of Paradise is classified as a TP scenario due to its shortest distance to the ignition location, which accounts for the highest level of risk it can be easily detected. Oroville is the second-nearest town that faces a high risk as well, but the risk perceived by residents could be misjudged due to a river close to the node, thus it was classified as a TN scenario. Compared to Oroville, the town of Chico has a lower wildfire risk due to its greater distance from the ignition location, but with higher risk awareness affected by the passing evacuees coming from Paradise. Hence, Chico is chosen to be simulated as a higher possibility for an FP scenario. Finally, the town of Willows is classified as a FN event due to its geographical distance from the ignition location.

4.1.2 Modeling Parameter Setup

For each evacuation scenario, the resident agents are randomly distributed with an arrival rate of one agent per second and a maximum quantity of 2000 in AnyLogic. The probabilities of select outputs for risk perception and risk mitigation measures undertaken by resident agents vary for different scenarios as shown in Table 3. Besides, this experiment assumes a random distribution for the agent flow split via different transportation means. Furthermore, the traffic flow exceeding a capacity of 100 vehicle agents will trigger transportation crowds, which are represented by agent queues (dashed lines marked in Figure 3).

Table 3. Probabilities of select outputs

	Risk perception undertaken	Risk mitigation undertaken
Scenario 1 (TP)	0.9	0.1
Scenario 2 (TN)	0.1	0.9
Scenario 3 (FP)	0.9	0.9
Scenario 4 (FN)	0.1	0.1

4.2 Simulation Outputs and Analysis

During the simulation, AnyLogic presents the number of agents disposed by modeling parameters in real-time. To evaluate the effectiveness of the proposed modeling solution, test scenarios were developed by adjusting relevant modeling parameters. Hereby, each evacuation scenario was run ten times in order to avoid biased simulation outputs. Simulation outputs with regard to test scenarios are summarized and analyzed in the following subsections.

4.2.1 The Influence of Transportation Crowds

The test scenario was developed with and without the modeling parameter of transportation crowds in order to investigate its influence on agent evacuation efficiency. In particular, the agent evacuation performance is evaluated by the travel time (measured by the modeling time in AnyLogic) for two types of vehicles, i.e., private and public vehicles, in each scenario (Table 4).

Table 4. Travel time (in seconds) for vehicles

	TP	TN	FP	FN
Private vehicles without crowds	2267	1863	2017	1920
Public vehicles without crowds	3983	3189	3463	3301
Private vehicles affected by crowds	7445	6188	7300	6410
Public vehicles affected by crowds	8032	7243	7785	7387

According to the simulation outputs, the evacuation efficiency in each scenario was negatively affected by the transportation crowds due to a longer travel time for both types of vehicles. The queuing time, however, slightly differ among these four scenarios, which have different numbers of vehicles driven through a route as shown in the GIS interface. The simulation outcome, as a result, validate the negative impact of transportation crowds on the evacuation efficiency. In this case, highway capacity must be increased to reduce the occurrence of transportation crowds.

4.2.2 The Effectiveness of Public Notification

To evaluate the effectiveness of public notification, this study used the statistics of disposed agents who stay in place due to not perceiving the risk or perceiving the risk but choosing to stay to defend their homes, as well as the agents who evacuate and reach a shelter using one of the four different transportation means in each scenario (Table 5).

Table 5. Statistics for agents disposed in different scenarios

	TP	TN	FP	FN
Risk not perceived – stay in place	195	1794	174	1825
Risk perceived – stay in place	243	118	1070	27
Walking	120	10	48	11
Bicycles	170	6	80	14
Private vehicles	347	18	165	42
Public vehicles	925	54	463	81

The simulation outputs indicate that public notification has a significant impact on the evacuation decision-making of resident agents. In the scenarios with public notifications (i.e., TP and FP scenarios), the number of agents who perceive the risk is greatly higher compared to the scenarios without notifications (i.e., TN and FN scenarios). Nevertheless, agents in the TP scenario prefer to evacuate after risk perceived and few agents intend to mitigate the risk. Conversely, in the FP scenario, a large portion of agents tend to take actions for risk mitigation instead of evacuating immediately. To conclude, public notification improves resident risk perception, but residents may still refuse to evacuate.

4.2.3 Comparison of Different Transportation Means

In this study, the evacuation efficiency is measured by the evacuation time per agent for different transportation means in each scenario. Several findings are drawn from Table 6: (1) evacuation by walking accounts for the lowest evacuation efficiency; (2) evacuation efficiencies of all transportation means in TP and FP scenarios are greatly higher than the efficiencies in TN and FN scenarios; and (3) evacuation efficiency of public vehicles is the highest even though their average velocities are slower than private vehicles. One possible explanation is that the loading capacity of public vehicles is the highest, consequently, more agents are loaded and able to approach a shelter at the same time.

Therefore, to improve the evacuation efficiency, it may be helpful to increase the availability of public transportation when evacuating residents in a wildfire emergency.

Table 6. Evacuation efficiency (in %) for different transportation means

	TP	TN	FP	FN
Walking	0.29	0.03	0.12	0.03
Bicycles	1.49	0.05	0.71	0.13
Private vehicles	4.66	0.29	2.26	0.66
(without crowds)	15.31	0.97	8.18	2.19
Public vehicles	11.52	0.75	5.95	1.1
(without crowds)	23.22	1.69	13.37	2.45

5 Conclusions and Future Research

Effective wildfire evacuation planning could help to improve resident evacuation efficiency during a wildfire emergency. Several studies to date focused on studying human behavior and evacuation performance during a wildfire. However, such modeling and simulation solutions to predict and assess evacuation performance in wildfire scenarios are still at their infancy. Therefore, this study proposed a modeling solution, using AnyLogic software, that integrates ABM and GIS to enable simulating and investigating the factors affecting outdoor evacuation performance during a wildfire. To that end, an experimental implementation was conducted to test several wildfire scenarios including: 1) a mandatory evacuation issued by safety officials for a true wildfire event, 2) a no-notice true wildfire event, 3) a mandatory evacuation issued for a false wildfire event, and 4) neither evacuation alert was issued nor a wildfire occurred.

The simulation outputs validated the practicality of our modeling solution. Several major findings are as follows: (1) transportation crowds negatively impact the evacuation performance, (2) public notification can enhance residents' risk perception, thus improve evacuation efficiency, and (3) public vehicles have the highest evacuation efficiency compared to other transportation means evaluated in this study. Several wildfire evacuation management strategies are suggested based on these findings. To conclude, this study assesses evacuation efficiency with regard to human life and transportation crowds in wildfire emergencies, which is expected to help in wildfire evacuation education and safety strategies. The proposed modeling solution provides a novel simulation approach that can used for wildfire safety management and effective evacuation planning for wildfire emergencies.

The proposed simulation framework has several limitations that should be noted. First, human evacuation behavior should be further studied and the modeling solution should be revised by adding or changing relevant modeling parameters to better assess human evacuation performance. Second, AnyLogic software is limited in terms of the number of modeling parameters that can be included in one scenario. Hence, this study fails to add the modeling elements that could simulate those four scenarios simultaneously. Third, due to the limitation of the current ABM modeling technique, this study emphasizes only simulating resident evacuation behavior. However, in reality, wildfire dynamics is a matter that could heavily impact the evacuation performance. To improve the viability of the proposed modeling solution, future studies should: (1) investigate human outdoor evacuation behavior; (2) simulate the interaction between residents living in different geographical regions; and (3) improve the modeling solution to enable simulating the wildfire dynamics and resident evacuation process simultaneously.

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